Thermodynamics(2) MEP2104

Course contents

- Second law of thermodynamics and energy conversion quality.
- Entropy.
- Exergy.
- Gas power cycles.
- Vapor power cycles.
- Refrigeration cycles.
- Thermodynamic relations.

REFERENCES AND SUGGESTED READINGS

1-. Thermodynamics An Engineering Approach. Yunus A. Cengel Michale A. Boles.

2- Fundamentals of thermodynamics. Borgnakke, Gordon John Van Wylen, and Richard E. Sonntag

3- A. Bejan. *Advanced Engineering Thermodynamics*.

4- K. Wark and D. E. Richards. *Thermodynamics.*

- The first law of thermodynamics (the principle of energy conservation).
- a process must satisfy the first law to occur However, satisfying the first law alone does not ensure that the process will actually take place.

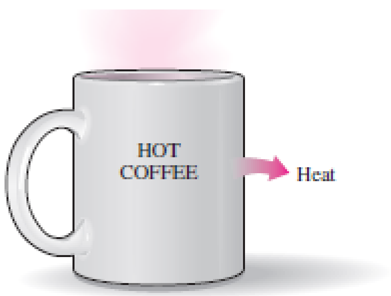


FIGURE 6–1
A cup of hot coffee does not get hotter in a cooler room.

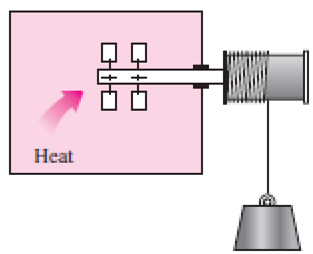


FIGURE 6–3
Transferring heat to a paddle wheel will not cause it to rotate.

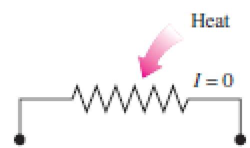


FIGURE 6–2
Transferring heat to a wire will not generate electricity.

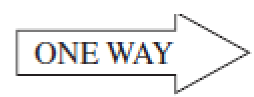


FIGURE 6–4
Processes occur in a certain direction, and not in the reverse direction.

The Second Law of Thermodynamics

- A process cannot occur unless it satisfies both the first and the second laws of thermodynamics.

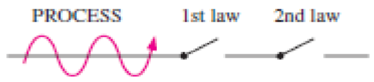


FIGURE 6–5

A process must satisfy both the first and second laws of thermodynamics to proceed.

- The use of the second law of thermodynamics is not limited to identifying the direction of processes, however.
- The second law also asserts that energy has *quality* as well as quantity.
- The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems.

Thermal Energy Reservoirs

- **Thermal energy reservoir** is a hypothetical body with a relatively large *thermal energy capacity* (mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature.

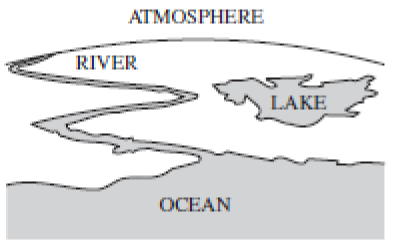


FIGURE 6–6
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

A body does not actually have to be very large to be considered a reservoir. Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be modeled as one. The air in a room, for example, can be treated as a reservoir in the analysis of the heat dissipation from a TV set in the room, since the amount of heat transfer from the TV set to the room air is not large enough to have a noticeable effect on the room air temperature.

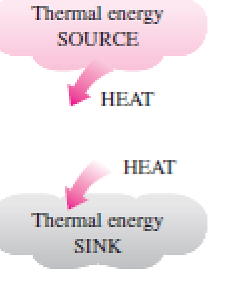


FIGURE 6–7
A source supplies energy in the form of heat, and a sink absorbs it.

Heat Engines

- work can easily be converted to other forms of energy, but converting other forms of energy to work is not that easy.
- but converting heat to work requires the use of some special devices. These devices are called **heat engines.**
- Heat engines differ considerably from one another, but all can be characterized by the following:

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).

2. They convert part of this heat to work (usually in the form of a rotating shaft).

3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).

4. They operate on a cycle.

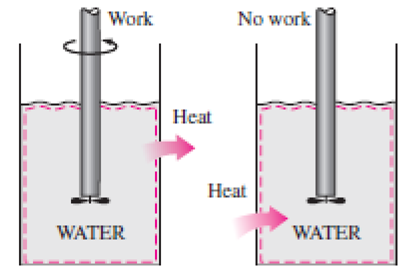


FIGURE 6–8

Work can always be converted to heat directly and completely, but the reverse is not true.

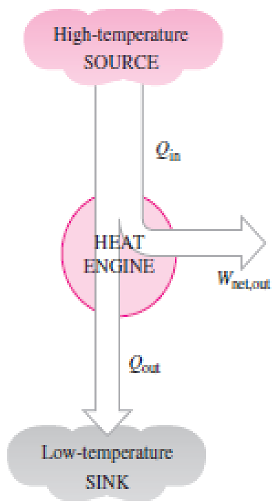


FIGURE 6–9

Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

The Second Law of Thermodynamics

Heat Engines

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low temperature sink (the atmosphere, a river, etc.)

W_{out} = amount of work delivered by steam as it expands in turbine

W_{in} = amount of work required to compress water to boiler pressure

$$W_{net,out} = W_{out} - W_{in} \quad \text{(kJ)}$$

$$W_{net,out} = Q_{in} - Q_{out} \quad \text{(kJ)}$$

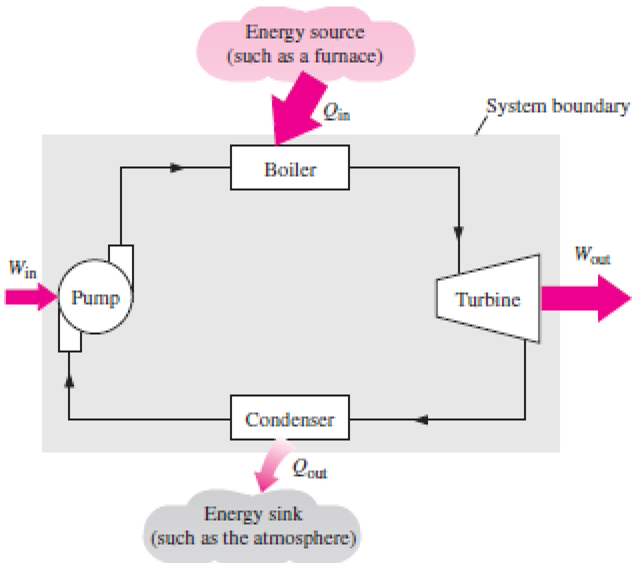


FIGURE 6–10

Schematic of a steam power plant.

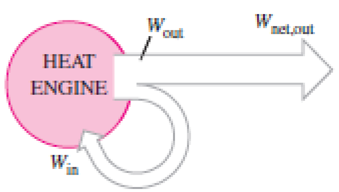


FIGURE 6–11

A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

Heat Engines

- **Thermal Efficiency:**

Thermal efficiency = net work output/total heat input

or

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

It can also be expressed as

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

since $W_{net,out} = Q_{in} - Q_{out}$.

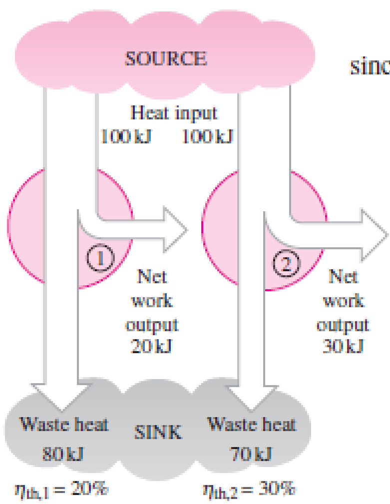


FIGURE 6–12
Some heat engines perform better than others (convert more of the heat they receive to work).

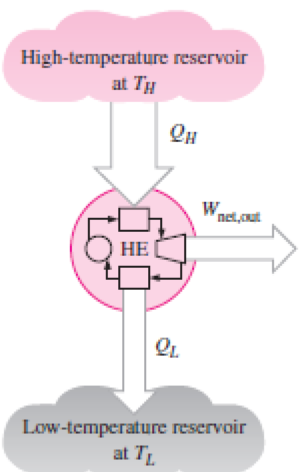


FIGURE 6–13
Schematic of a heat engine.

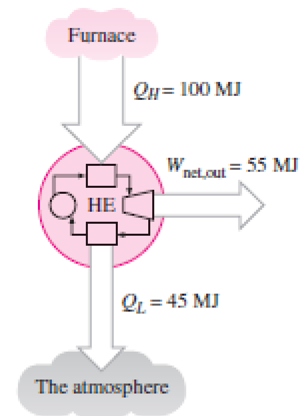


FIGURE 6–14
Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.

Heat Engines

Can We Save Q_{out}?

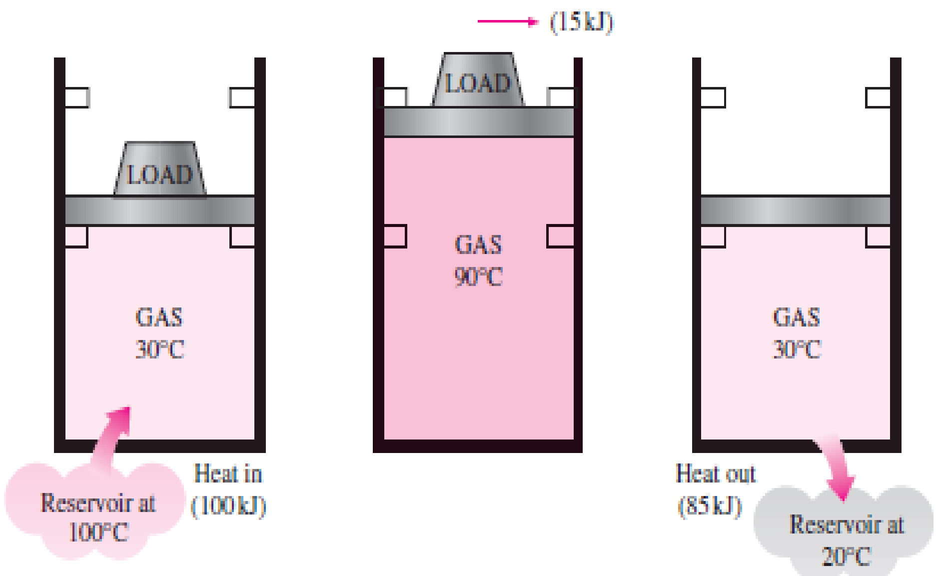


FIGURE 6–15

A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink.

Heat Engines

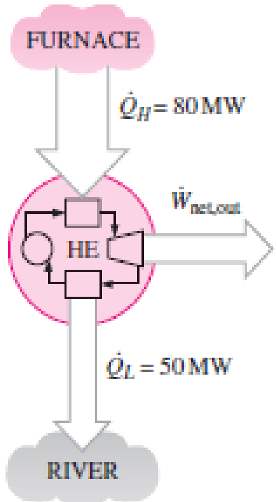


FIGURE 6–16

Schematic for Example 6–1.

EXAMPLE 6–1 Net Power Production of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

Solution The rates of heat transfer to and from a heat engine are given. The net power output and the thermal efficiency are to be determined.

Assumptions Heat losses through the pipes and other components are negligible.

Analysis A schematic of the heat engine is given in Fig. 6–16. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low-temperature reservoir. The given quantities can be expressed as

$$\dot{Q}_H = 80 \text{ MW} \quad \text{and} \quad \dot{Q}_L = 50 \text{ MW}$$

The net power output of this heat engine is

$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = (80 - 50) \text{ MW} = \mathbf{30 \text{ MW}}$$

Then the thermal efficiency is easily determined to be

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{30 \text{ MW}}{80 \text{ MW}} = \mathbf{0.375} \text{ (or } 37.5\%\text{)}$$

Discussion Note that the heat engine converts 37.5 percent of the heat it receives to work.

Heat Engines

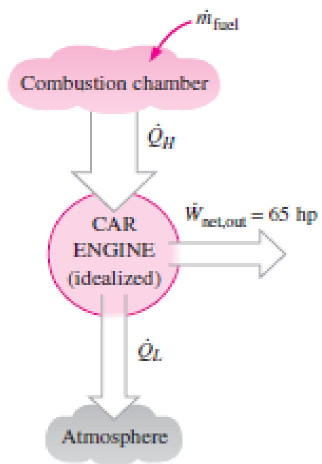


FIGURE 6–17
Schematic for Example 6–2.

EXAMPLE 6–2 Fuel Consumption Rate of a Car

A car engine with a power output of 65 hp has a thermal efficiency of 24 percent. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm (that is, 19,000 Btu of energy is released for each lbm of fuel burned).

Solution The power output and the efficiency of a car engine are given. The rate of fuel consumption of the car is to be determined.
Assumptions The power output of the car is constant.
Analysis A schematic of the car engine is given in Fig. 6–17. The car engine is powered by converting 24 percent of the chemical energy released during the combustion process to work. The amount of energy input required to produce a power output of 65 hp is determined from the definition of thermal efficiency to be

$$\dot{Q}_H = \frac{\dot{W}_{\text{net,out}}}{\eta_{\text{th}}} = \frac{65 \text{ hp}}{0.24}\left(\frac{2545 \text{ Btu/h}}{1 \text{ hp}}\right) = 689{,}270 \text{ Btu/h}$$

To supply energy at this rate, the engine must burn fuel at a rate of

$$\dot{m} = \frac{689{,}270 \text{ Btu/h}}{19{,}000 \text{ Btu/lbm}} = \mathbf{36.3 \text{ lbm/h}}$$

since 19,000 Btu of thermal energy is released for each lbm of fuel burned.
Discussion Note that if the thermal efficiency of the car could be doubled, the rate of fuel consumption would be reduced by half.

The Second Law of Thermodynamics:
Kelvin–Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

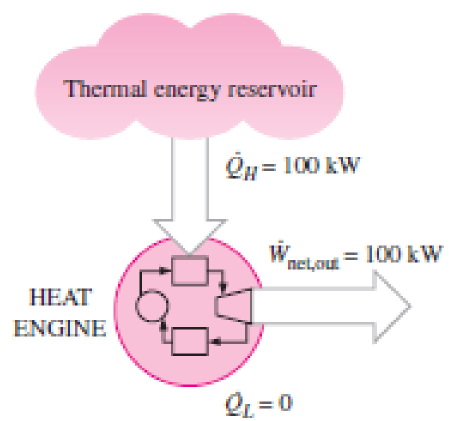


FIGURE 6–18

A heat engine that violates the Kelvin–Planck statement of the second law.

REFRIGERATORS AND HEAT PUMPS

Coefficient of Performance:

$$\mathrm{COP_R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\mathrm{net,in}}}$$

$$W_{\mathrm{net,in}} = Q_H - Q_L \qquad \text{(kJ)}$$

Then the COP relation becomes

$$\mathrm{COP_R} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

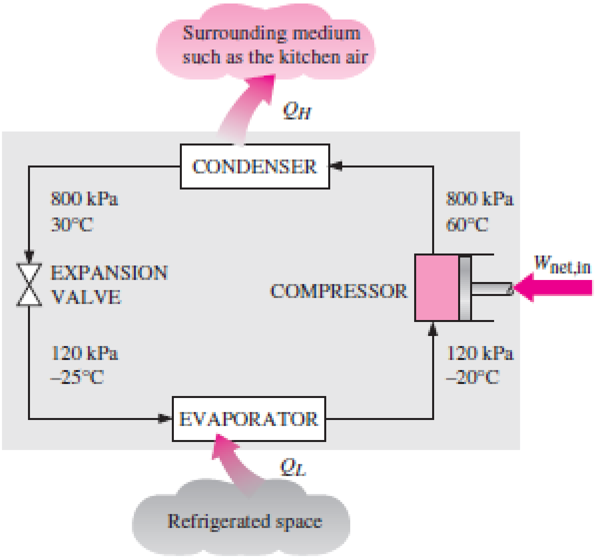


FIGURE 6–19
Basic components of a refrigeration system and typical operating conditions.

Heat Pumps

$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\mathrm{net,in}}}$$

which can also be expressed as

$$\mathrm{COP_{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$\mathrm{COP_{HP}} = \mathrm{COP_R} + 1$$

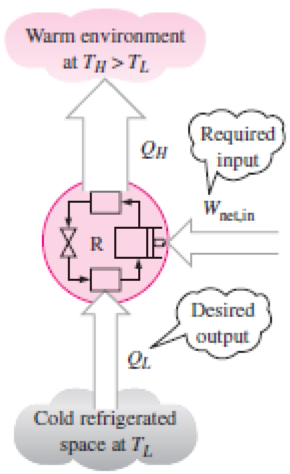


FIGURE 6–20
The objective of a refrigerator is to remove Q_L from the cooled space.

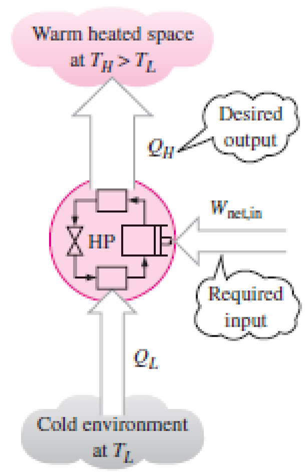


FIGURE 6–21
The objective of a heat pump is to supply heat Q_H into the warmer space.

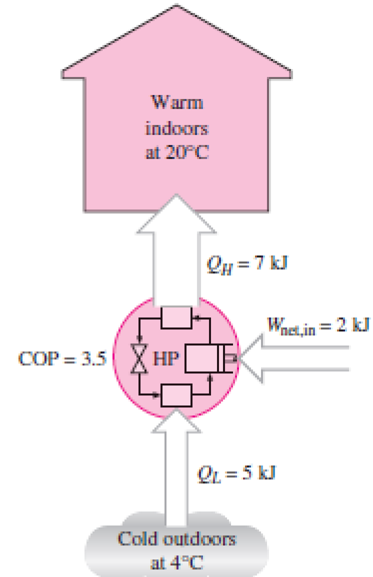


FIGURE 6–22
The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.

EXAMPLE 6–3 Heat Rejection by a Refrigerator

The food compartment of a refrigerator, shown in Fig. 6–24, is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (*a*) the coefficient of performance of the refrigerator and (*b*) the rate of heat rejection to the room that houses the refrigerator.

Solution The power consumption of a refrigerator is given. The COP and the rate of heat rejection are to be determined.

Assumptions Steady operating conditions exist.

Analysis (*a*) The coefficient of performance of the refrigerator is

$$\mathrm{COP_R} = \frac{\dot{Q}_L}{\dot{W}_{\mathrm{net,in}}} = \frac{360\ \mathrm{kJ/min}}{2\ \mathrm{kW}}\left(\frac{1\ \mathrm{kW}}{60\ \mathrm{kJ/min}}\right) = \mathbf{3}$$

That is, 3 kJ of heat is removed from the refrigerated space for each kJ of work supplied.

(*b*) The rate at which heat is rejected to the room that houses the refrigerator is determined from the conservation of energy relation for cyclic devices,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\mathrm{net,in}} = 360\ \mathrm{kJ/min} + (2\ \mathrm{kW})\left(\frac{60\ \mathrm{kJ/min}}{1\ \mathrm{kW}}\right) = \mathbf{480\ kJ/min}$$

Discussion Notice that both the energy removed from the refrigerated space as heat and the energy supplied to the refrigerator as electrical work eventually show up in the room air and become part of the internal energy of the air. This demonstrates that energy can change from one form to another, can move from one place to another, but is never destroyed during a process.

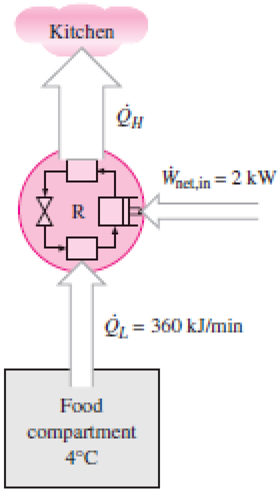


FIGURE 6–24
Schematic for Example 6–3.

EXAMPLE 6–4 Heating a House by a Heat Pump

A heat pump is used to meet the heating requirements of a house and maintain it at 20°C. On a day when the outdoor air temperature drops to −2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (*a*) the power consumed by the heat pump and (*b*) the rate at which heat is absorbed from the cold outdoor air.

Solution The COP of a heat pump is given. The power consumption and the rate of heat absorption are to be determined.

Assumptions Steady operating conditions exist.

Analysis (*a*) The power consumed by this heat pump, shown in Fig. 6–25, is determined from the definition of the coefficient of performance to be

$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP}}} = \frac{80{,}000 \text{ kJ/h}}{2.5} = \mathbf{32{,}000 \text{ kJ/h}} \text{ (or 8.9 kW)}$$

(*b*) The house is losing heat at a rate of 80,000 kJ/h. If the house is to be maintained at a constant temperature of 20°C, the heat pump must deliver heat to the house at the same rate, that is, at a rate of 80,000 kJ/h. Then the rate of heat transfer from the outdoor becomes

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net,in}} = (80{,}000 - 32{,}000) \text{ kJ/h} = \mathbf{48{,}000 \text{ kJ/h}}$$

Discussion Note that 48,000 of the 80,000 kJ/h heat delivered to the house is actually extracted from the cold outdoor air. Therefore, we are paying only for the 32,000-kJ/h energy that is supplied as electrical work to the heat pump. If we were to use an electric resistance heater instead, we would have to supply the entire 80,000 kJ/h to the resistance heater as electric energy. This would mean a heating bill that is 2.5 times higher. This explains the popularity of heat pumps as heating systems and why they are preferred to simple electric resistance heaters despite their considerably higher initial cost.

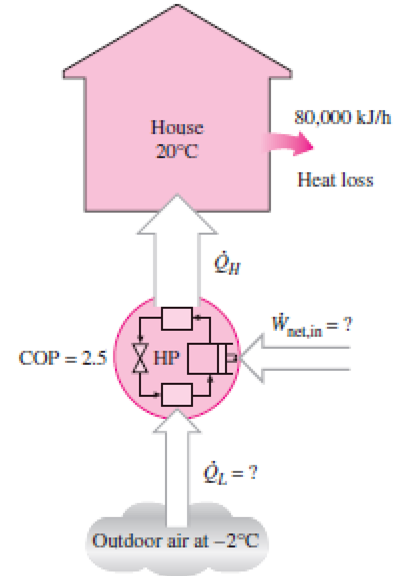


FIGURE 6–25
Schematic for Example 6–4.

The Second Law of Thermodynamics: Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

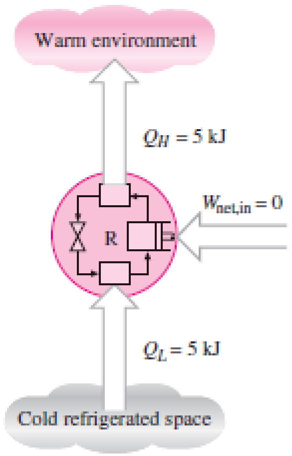
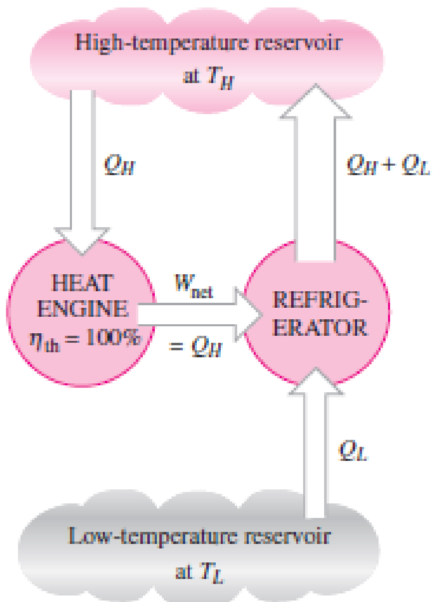


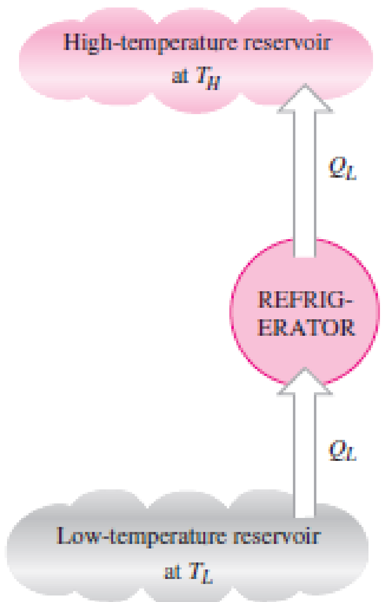
FIGURE 6–26

A refrigerator that violates the Clausius statement of the second law.

Equivalence of the Two Statements



(*a*) A refrigerator that is powered by a 100 percent efficient heat engine



(*b*) The equivalent refrigerator

FIGURE 6–27

Proof that the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

PERPETUAL-MOTION MACHINES

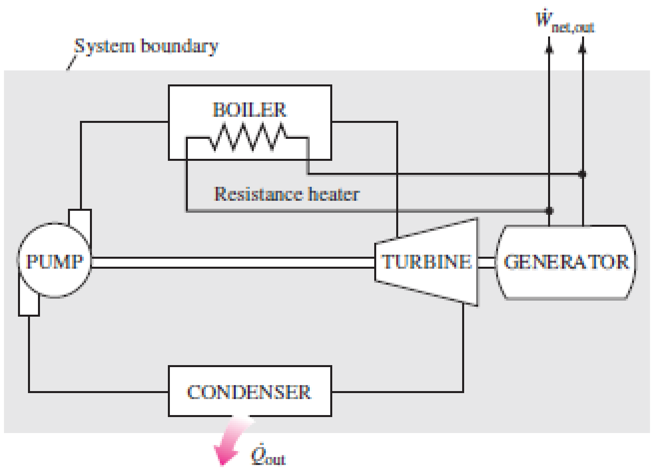


FIGURE 6–28

A perpetual-motion machine that violates the first law of thermodynamics (PMM1).

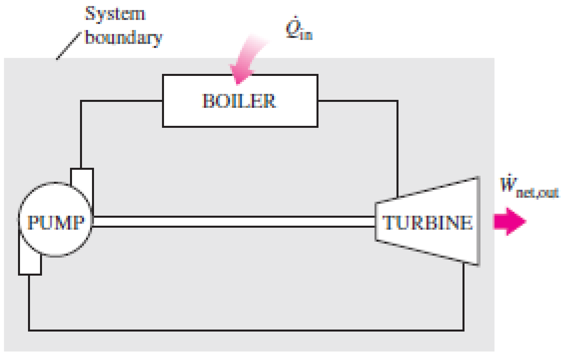


FIGURE 6–29

A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

The Second Law of Thermodynamics